Thickened Tailings Beach Deposition.
Field Observations and Full-Scale Flume Testing

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ABSTRACT

It is a matter of observational experience that slurry flow confines itself into a self-formed channel to find its way down the beach, Williams (2001). It is believed that the channel flow characteristics determine the overall beach slope. The present research project was undertaken to understand the flow characteristics of the channelized tailings. All tests were carried out in controlled conditions in a full-scale experimental flume installed at a mine site, using the flow of fresh mine tailings from the discharge pipeline. For each test, a limiting equilibrium bed slope was obtained. Velocity and density fluctuations and also the average profile with depth were recorded. It is thought that this is the first time that profile measurements on a full scale slurry flow of this type have been carried out. Results from the tests cover many issues and aspects of the on-going work. The mechanisms involved in beach formation and development as well as the occurrence of laminar and turbulent slurry flow regimes on a real stack and the affecting parameters on beach slope, have been investigated in detail. A summary of the key data and the preliminary conclusions that can be drawn have been presented.

1. INTRODUCTION

As the tailings beach slope value has direct and significant impact on the capacity of the impoundment and the height of the dam wall in tailings disposal schemes, estimation and prediction of this slope has been the target of much research work.

Recent advances in thickener technology that enable the mining industry to produce tailings with solids contents greater than 60%, has caused the stacked thickened tailings schemes (Central Thickened Discharge (CTD) and Down-Valley Discharge (DVD)) to have even wider application.

Prediction of the beach slope is the basis for design of stacked tailings disposal schemes but to date there is no rational method of prediction based on theory.

Most of the research effort over the last twenty years has been allocated to the flow of segregating slurries and the beach profile formed by segregating tailings. Non-segregating slurries are essential for stacked tailings disposal. By definition, hydraulic sorting is not an issue with non-segregating tailings since it does not occur. There is both field; Robinsky (1975), Williams (1992), and laboratory; Blight (1987) evidence that non-segregating tailings have a planar, i.e. non-concave, beach slope. In the context of the master profile equation; Blight and Bentel (1983), this corresponds to n =1.

Furthermore, there has been no general agreement on the mechanism of beach deposition and formation. Much of the research has concentrated on observations in small-scale laboratory flumes since work at this level is relatively easy to perform.

The current research work described in this paper, by contrast, draws on the observation of full-scale beaching behaviour. Williams and Meynink (1986), and Williams (1992, 2001) suggest that two distinct flow regimes exist on a tailings beach, namely a narrow, confined, turbulent-flow channel that conveys tailings to a localised area of broad, laminar sheet flow where deposition occurs. De Groot et al (1988) and Winterwerp et al. (1990) also observed the channel phenomenon and recognised its importance in the process of dredged sand deposition.

The work was undertaken at the active stack of Peak Gold Mines at Cobar in New South Wales, Australia.

The first part of the paper deals with different mechanisms, processes and patterns of beach formation and development that were observed, the conditions in which laminar or turbulent flow of non-segregating slurry can occur on a stack and the characteristics of the beach developed under each regime.

In the second part, the experimental arrangement and the results from full-scale flume tests are presented and discussed.

2. BEACH FORMATION AND DEVELOPMENT. VISUAL OBSERVATIONS OF FULL SCALE STACK

2.1. Occurrence of Laminar Flow Regime in the Tailings Deposition Process

The flow is laminar if the viscous forces are strong relative to the inertia forces. That means that viscosity plays a significant part in determining flow behaviour.

The ratio of inertia forces to viscous forces is expressed as Reynolds number. The form of Reynolds number used for open channel flow is:

$$R_e = \frac{UR}{\nu} \qquad [1]$$

where U = velocity
ν = kinematic viscosity
R = hydraulic radius

For sheet flow, where the width is very large compared to the depth, the equation can be written as:

$$R_e = \frac{Uh}{\nu} \qquad [2]$$

where h = depth.

The transition from laminar to turbulent flow in open channels can be expected in the range R_e = 500 to 2000.

2.2. Mechanics of Laminar Flow and Deposition

In laminar flow, fluid particles move in definite smooth, continuous paths in straight lines. There is no significant transverse mixing or momentum exchange between the layers of sliding laminar flow as the fluid flows point-to-point. Therefore there will be no vertical component of velocity to compensate for the settling velocity of the solid particles. Thus a density profile will form in the flow as it moves forwards.

In the case of sheet and fan (non-channelized) laminar flow, the lateral expansion and forward motion of the sheet can be defined as the sliding layers of slurry riding over one another.

As the laminar sheet moves and spreads out, the depth of the flow decreases and the slurry sheet becomes thinner and thinner. The laminar flow regime also provides suitable conditions for a density profile to form in the slurry layer through the mechanism of zone-settling, which in turn will causes an increase in solids percent, shear strength and viscosity of the lower layers. Eventually the shear strength of the slurry layer which is the nearest layer to the stationary bed, increases to the level that it cannot accompany the rest of the flow in motion and it stops. The next slurry layer (the layer right above the recently halted layer) in turn, contacts the bed and takes the place of the previous layer and the movement continues. Thus, the thickness of the sheet flow gradually reduces as the flow moves forward and spreads laterally, until the surface layer contacts the stationary bed and movement abruptly ceases. This procedure can be shown as Figure 1. The released water appears in the form of supernatant running water on top of the last layer, see Figure 2.

The slope stability of sheet flow is well understood in geomechanics by the following formula; Blight and Bentel (1983), Williams (2001).

$$\sin(i) = \frac{S_u}{\gamma d} \qquad [3]$$

where i = slope angle

S_u = undrained shear strength

γ = slurry density

d = sheet thickness measured normal to the slope

For a particular slurry with known undrained shear strength and density, the problem with the above equation is that the sheet thickness, d is not known, so that with any assumed value for the sheet thickness, any equilibrium slope $\sin(i)$ can be obtained.

As illustrated in Figure 1, the cessation in the motion of a sheet flow (regardless of the discharge rate and total depth of the flow), would not occur abruptly over the full depth of the flow, but starts from the lowermost layer (next to the stationary bed) with a depth of h_1 and progressively influences the whole depth of the flow, layer by layer. Therefore the thickness of the sheet in equation [3] should always be considered $d = h_1$ (and not $d = H$), regardless of what the initial total depth of the flow is. But it must also be understood that because of the density profile which forms in laminar sheet flow, the density and shear strength of the layers which come to rest, are not necessarily the same density and shear strength of the original slurry mixture.

Therefore, in laminar flow the equilibrium slope at which the slurry layers come to rest is the result of a balance achieved between the increasing density and shear strength on the one hand and the thickness of the lowest layer on the other hand.

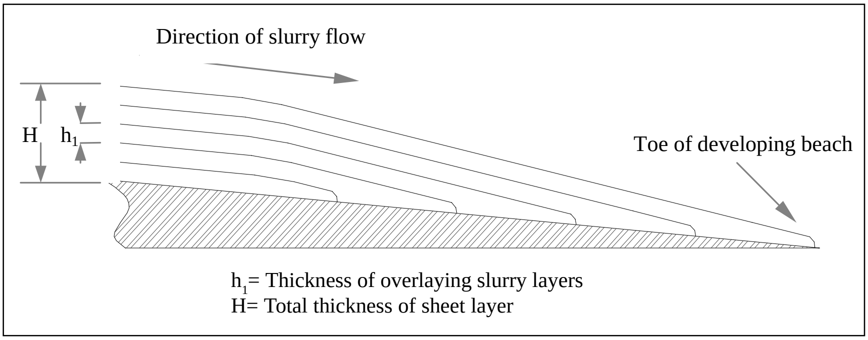

Figure 1: Motion of non-canalized (sheet or fan) laminar slurry flow.

Figure 2: The supernatant running water at the toe of the beach on top of the last layer.

From this explanation it can be concluded that, for a particular slurry mixture discharged over a horizontal surface in the form of separate batches, the thickness of the subsequent layers which come to rest (h_1) and also the overall equilibrium slope, $\sin(i)$, are independent of flowrate and may be one of the constitutional properties of the slurry as a function of particle size, percent solids, rheology, zone-settling velocity of the tailings, etc. This is a topic which requires further investigation and laboratory tests.

The two-dimensional beach formed and developed by the above-mentioned mechanism in small scale laboratory flumes, has been the basis of much research work about the concavity and master profile of tailings beaches, Blight et al. (1985) and Kuepper (1991). Kuepper (1991) and Kuepper et al. (1992), found that the slope of the beaches formed from laminar sheet flow in laboratory flumes is steeper than their field counterparts and should not be taken as indicative of the corresponding full-size stack beach slope.

2.3. How Far Can Laminar Flow Go?

If a very large area of tailings stack is eventually to be developed it can be intuitively understood that this will not occur over the full 360^0 and the full radial distance simultaneously. This would require a progressively thinner and thinner sheet each day, and a progressively steeper and steeper slope (according to equation [3]). Furthermore, the radial velocity would have to also increase since the time for zone settling within a layer is fixed and the flow must reach the outermost perimeter of the area before this occurs.

This is simply not seen in practice. Instead, the tailings concentrate their efforts into a relatively narrow radial arc. In this way the layer thickness can be maintained and a greater radial distance can be achieved. The tendency for concentration – channelisation - of flow is thus inevitable, even with laminar flow. This was commonly observed on the Peak Stack, Figure 3.

The typical parameters for flow of the sort shown in Figure 3 at Peak were:

$U < 0.2$ m/s

$h = 20 - 30$ mm

$\nu = 15 \times 10^{-6}$ m^2/s

Hence, Reynolds numbers (equation [2]) of 270 to 400, clearly still in the laminar range.

Figure 3: Overriding laminar rolling waves in channelised sheet flow.

2.4. Occurrence of Turbulent Flow Regime in the Tailings Deposition Process

A key constraint on long distance travel of the tailings is clearly the issue of zone settling and the limited time available in laminar flow before this occurs. This can only be overcome by a transition to turbulent flow.

The flow is turbulent if the viscous forces are weak relative to the inertial forces. In the turbulent flow the fluid particles move in irregular paths which are neither smooth nor fixed but still represent the forward motion of the fluid. In turbulent regime the weight of the solid particles is continuously supported by the fluid. Turbulence is the most important factor in the suspension of solids particles. The zone-settling velocity of the solids is counter-balanced by the irregular motion of the fluid particles introduced by the turbulent velocity components.

The laminar/turbulent transition is in the Reynolds number range 500 to 2,000. From the data given above, for a given slurry the transition from laminar to turbulent flow can only occur with substantial increases in velocity. This necessitates the concentration of flow into self-formed channels. This is indeed what is seen. Figures 4 to 9 show time lapse photographs at an advancing tongue of tailings on the Peak stack. The development of a concentrated turbulent channel, as indicated by the standing waves, can clearly be seen.

The hydraulic radii of such channels were typically around 25 – 35 mm and the velocities 1.0 - 1.5 m/s giving Reynolds numbers of 2,000 to 4,000.

Since it is observed on a large scale that it is turbulent flow channels that transport the tailings to the distal parts of the stack where localised sheet flow deposition occurs, the slope of such channels are the controlling macro influence on the overall stack slope.

This is the slope that is needed as a design parameter. This leads to the second part of the paper which describes test work on turbulent channel flow.

Figure 4: 0 min.

Figure 5: 1 min. 10 sec.

Figure 6: 2 min. 22 sec.

Figure 7: 3 min. 54 sec.

Figure 8: 5 min. 36 sec.

Figure 9: 8 min. 58 sec.

3. FULL-SCALE FLUME TESTS

To better understand the characteristics and behaviour of channelized tailings flow and also determine the regime of the flow at limiting equilibrium slope conditions, a series of tests were carried out in a full-scale experimental flume installed at the Peak mine site.

What distinguishes these tests from the flume tests of previous researchers is (a) the size of the flume and (b) its ability to take up to the full tailings output stream from the plant. The intention was to “capture” a length of naturally formed turbulent channel to permit detailed observations of its dimensions and flow charactertics.

To the knowledge of the authors, there are very few experimental data available on open channel flow of thickened slurries. Two pioneering papers in this regard describe the research done at Delft Hydraulics by de Groot et al. (1988) and Winterwerp et al. (1990). There are no values on the segregation threshold of the slurries used in these studies, but from the concentration data it is likely that the experimental data are for non-segregating thickened slurries flow. Winterwerp et al. (1990) states that “The main problem appears to be the lack of accurate experimental data to verify theory”.

3.1. Experimental Setup and Test Program

As thickened tailings are a viscous fluid with non-Newtonian behaviour, scale effects can be significant and are a serious issue in the study of the phenomenon. To avoid any scaling effects, all tests were carried out in a large straight, metal framed flume with continuous slurry flow from the effluent tailings pipeline which carries the tailings from the thickener underflow to the tailings storage area.

Maximum slurry flow rate from the plant was about 26 L/s in the main pipeline. A separate 150 mm diameter HDPE pipe was branched from the main pipeline to divert the slurry flow to the inlet box of the flume, the inlet box was designed at the beginning of the flume to absorb and dissipate the extra energy of the in-coming flow before entering the flume.

Running all the tests at site near to the source of fresh tailings, avoided problems with recirculation of the slurry through a pumping system which can result in structural breakdown of the slurry and affect the viscosity and rheology of the slurry.

Accurate adjustment of flowrate was possible by a combination system of a butterfly valve at the upstream end of the 150 mm HDPE pipe (near to the junction to the main pipeline) and a diaphragm valve at the downstream end of the pipe right above the inlet box. A bypass system (HDPE pipe with another butterfly valve) was also added to facilitate the regulation of the flow and to work as a drain during flushing.

The experimental flume was 10m long, 1m wide and 0.5 m deep. These dimensions for the flume were selected to satisfy various considerations such as adequate length for the development of the flow inside the flume, providing enough lateral freedom for the flow to form its own beach and meandering longitudinal channel, and the required depth for the self-formed channel and beach to form inside the flume by deposition of solids materials in the bed. As a consequence of the latter freedoms, no scaling of the results was necessary. The flume, as previously noted, simply served to “capture” a full-scale section of the channel. This is an important distinction from laboratory size flume tests. Structural and construction limitations were also considered in the design of the flume.

An outlet box of a known volume (1.2 m × 1 m × 0.5 m) with a sliding gate at one of the side walls was designed at the downstream end of the flume for measurement of the average flowrate by letting it fill the box and recording the filling time.

The body and structure of the flume, upstream and downstream supports, inlet and outlet boxes were constructed from steel box channels and sheets, the inside of the flume was lined with 15 mm thick plywood to prevent any interference with the electromagnetic field created by the velocity probe. The downstream support of the flume was so designed that variation and changes in the longitudinal slope of the flume was possible from the downstream end. Figure 10 shows the general view of the experimental flume.

The measurement of velocity fluctuations at different locations in the flow was possible by an immersible E-30 type programmable electromagnetic sensor and control unit, developed and manufactured by Delft Hydraulics. The probe had an ellipsoid shape with a diameter of 33 mm and a thickness of 11mm. The velocity probe was initially calibrated in Delft Hydraulics laboratory and calibration equations were obtained for the velocity range (0 to 1m/s) and (0 to 2.5 m/s). Prior to each test run the zero setting of the probe was checked and reset against a still tailings sample.

The solids percent (concentration) at different depths of the flow were measured with a conductivity type concentration meter probe developed and manufactured by Delft Hydraulics. The rod shaped concentration probe had a tip dimension of 2 mm × 10 mm × 10 mm. The initial calibration of the density probe was also done at Delft Hydraulics laboratory and prior to each test the calibration was checked in the field against solids free decant water obtained from fresh tailings. The percent solids of this sample was introduced to the system as zero concentration.

Figure 10: General view of the experimental flume installed at the mine site.

Both velocity and density probes were connected to the control units via coaxial cables and the signals were sent to a laptop computer through an A/D board and data acquisition system, to be recorded and stored. Figures 11 and 12 shows the velocity and density probes and their control units.

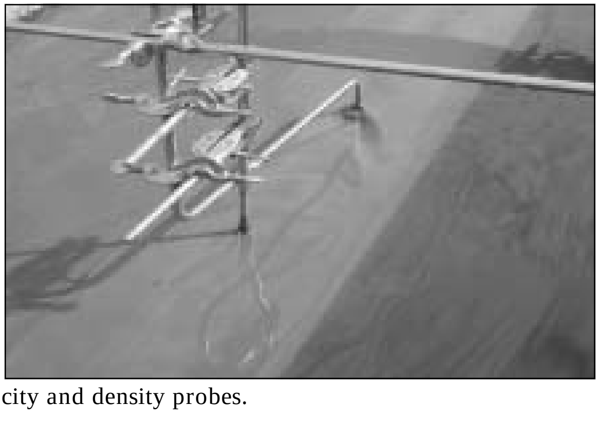

Figure 11: Velocity and density probes.

Figure 12: Control units for velocity and density probes.

Velocity and density fluctuations were measured and recorded for 30s from each measuring point with a sampling frequency of 10 Hz. Data collection and management of the recorded velocity and density data was through USB based analogue data collection computer software purchased from Delft hydraulics. The experimental tests were arranged in two different stages as follows.

3.1.1. Stage 1. Experiments on full-scale self-formed tailings channel in horizontal flume

For this stage of the experimental tests the flume was set to a horizontal position and the valves opened to let slurry flow of a specific percent solids and discharge rate enter the flume from the upstream inlet box. The slurry was allowed to build up its own beach and channel of certain shape and slope (by depositing solids materials on the bed). After the stabilization of the beach and flow in the flume, the self-formed channel dimensions were measured. The velocity and density fluctuations at different depth were recorded and the time average velocity and density profiles with depth at different sections along the channel were obtained. The test was repeated for different flowrates. Figure 13 illustrates the channel formation inside the flume, confirming the independence of the channel from the sides of the flume.

Figure 13: Self-formed slurry channel inside the experimental flume.

Slurry samples were taken in each series of tests for rheology and solids content analysis. Photography and video recording was taken during all tests.

At this stage of the tests the slurry was let to build up its own bed and channel, as it flows through the rectangular flume. But problems were encountered with the stability of self-formed channel. It was found that any small variations, even small disturbances or turbulence generated downstream of the density or velocity probes, were enough to initiate local erosion which formed a hydraulic jump that intensified the bed erosion and ultimately destroyed the stability of the whole system. Thus although an equilibrium channel was formed, with the required balance between flowrate, slope and zero further deposition, the act of measurement was destructive and prevented the collection of full sets of data.

3.1.2. Stage 2. Experiments on semi-circular channels of specific dimensions with variable bed slope

A second stage of the experimental tests was arranged to overcome the problem of instability during measurement. Measurement of channel dimensions in the Stage 1 tests, and on the stack itself, showed that semi-circular profiles could be fitted to the shapes and dimensions of the channels, with a very good approximation. Two different size PVC pipes (D=360 mm, D=424 mm) were selected as artificial channels for the second stage of the tests. These pipes were cut in half (length wise) and assembled inside the flume. To create boundary roughness the same as the fine tailings roughness, epoxy resin was used to glue sand particles with nominal diameter less than 1.18 mm to the inside wall of the half-pipe channel. As slurry flow passed through the half-pipe section for the first time, finer particles of tailings were trapped between the coarser sand particles attached to the wall, and covered all the inside surface of the pipe, creating a uniform smooth surface of tailings materials with the same roughness as the tailings itself. Figure 14 shows the flume during the second stage of the tests.

Figure 14: Experimental flume at the second stage of the tests.

The slope of the flume was set initially to a relatively steep slope that caused supercritical accelerating flow to occur in the channel. Then the slope was reduced gradually until sedimentation along the channel just started to occur and a steady uniform flow developed within the channel (with no further deposition on the bed). The bed of the channel was continuously checked for deposition of solids during each set of subsequent measurements. At this condition the depth of flow, surface profile along the channel, velocity profile with depth, density profile with depth and the equilibrium slope were measured. Problems with hydraulic jumps were avoided.

3.2. Experimental Results

A summary of the flume results are presented in this paper. Table 1 shows the flow characteristics and equilibrium slope for the test runs in the semi-circular channel. The solid particles in the slurry had $D_{50} = 10\mu m$ and the segregation threshold limit for the tailings was 42% solids. Typical slurry densities were in the range 54 – 58% solids. Thus the solids content of the flow was well beyond the segregation threshold limit during the tests. The temperature of tailings during the testes run was 30 to 33 ^0C . Rheological behaviour and particle size distribution of the tailings are shown on figure 15, 16.

The solids particles had specific gravity of $G_s = 2.78$ which was used for calculations of slurry density. In the calculation of Reynolds number, the Bingham plastic viscosity was used. Average velocity and the hydraulic radius of the cross-section in each test were also used.

The measurement section was 5.5 m downstream of the inlet section. The points on the velocity and density profiles in Figure 17, 18 are the time average values from a 30 s recording of the fluctuations with a sampling frequency of 10 Hz.

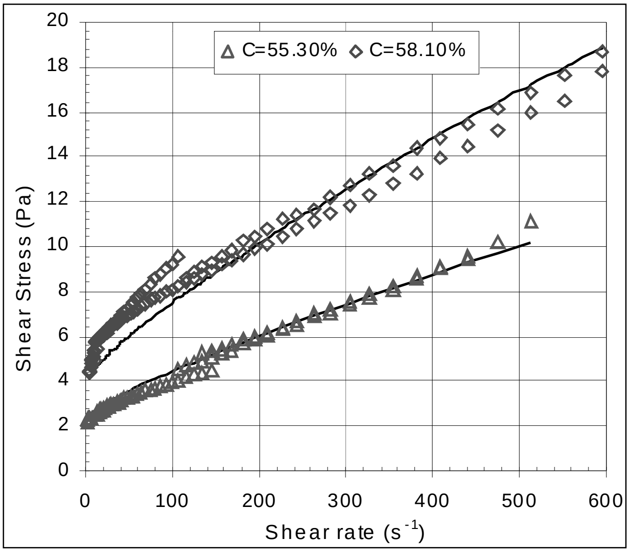

Figure 15: Rheology of peak tailings.

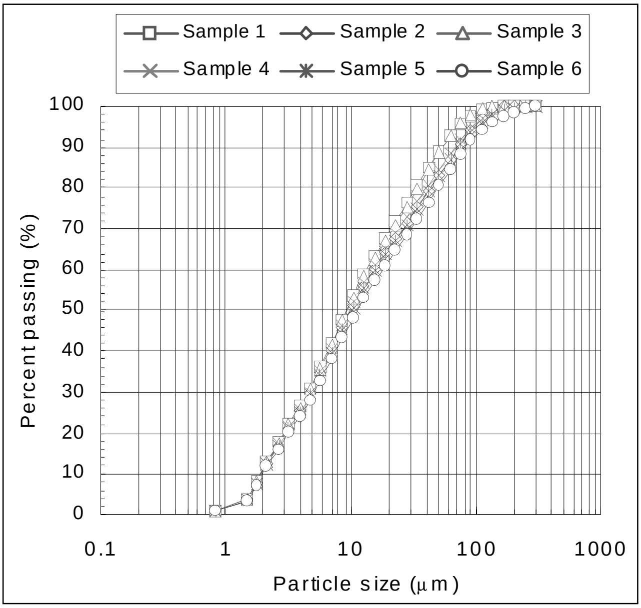

Figure 16: Particle size distribution of the tailings.

Q (lit/s)	Slope (S) %	Solid Percent (C) %	Depth (d) (mm)	Pipe Diameter (mm)	Slurry Density (kg/m3)	Average Velocity (m/s)	Froude Number F	Reynolds Number R_e
4.0	3.72	55.2	30	360	1547	0.99	2.21	1983
7.2	2.93	53.7	36	360	1523	1.36	2.77	4384
8.0	3.00	57.7	43	414	1587	1.08	2.01	2290
11.5	2.60	55.1	54	414	1545	1.11	1.85	4033
14.5	2.53	56.1	57	414	1560	1.30	2.09	4464
15.5	2.00	56.1	57	414	1560	1.39	2.24	4772
16.1	2.31	58.2	67	360	1595	1.23	1.82	3537
19.0	1.68	55.5	73	414	1552	1.19	1.68	5478

Table 1: Flow characteristics and regime of flow in equilibrium slope condition (semi-circular channel tests).

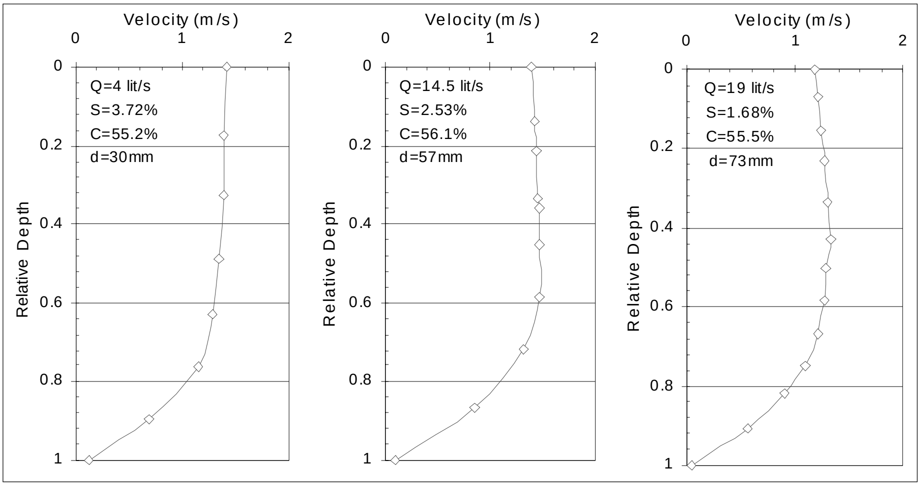

Figure 17: Velocity profile with depth for selected of the tests (equilibrium slope condition).

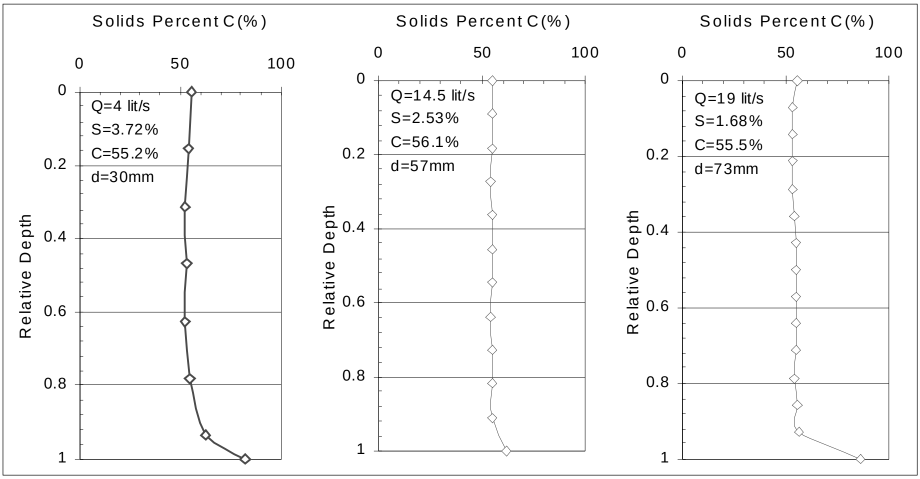

Figure 18: Density profile with depth for some of the tests (equilibrium slope condition).

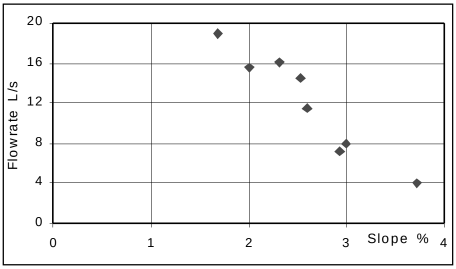

Figure 19: Slope vs Flowrate.

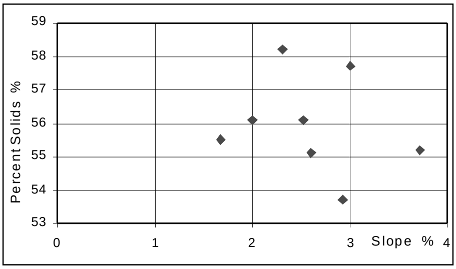

Figure 20: Slope vs Percent Solids.

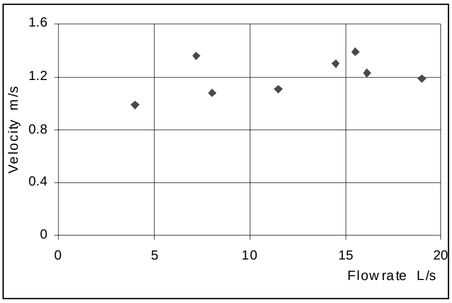

Figure 21: Average Velocity vs Flow Rate.

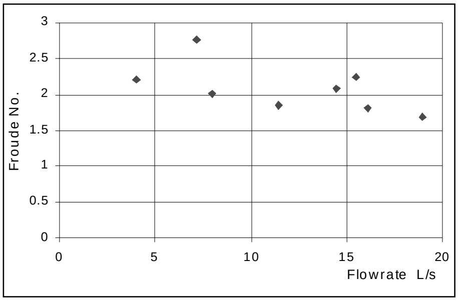

Figure 22: Froude No. vs Flow Rate.

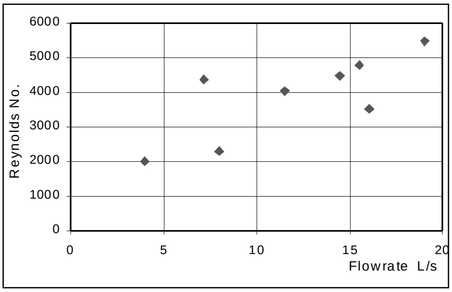

Figure 23: Reynolds No. vs Flow Rate.

- Plots of other parameters are shown on Figures 19-23 specifically:

Slope vs Flow Rate, Figure 19
Slope vs Percent Solids, Figure 20
Average Velocity vs Flow Rate, Figure 21
Froude No. vs Flow Rate, Figure 22
Reynolds No. vs Flow Rate, Figure 23

4. DISCUSSION

The Reynolds numbers in the range 1983 - 5478 confirmed that turbulent conditions existed in all of the tests. The velocity profiles were all very similar and indicate that there was a substantial moving shearing bed over the bottom 30% of the profile but uniform average horizontal velocity, also consistent with turbulent flow, above that. The density profiles confirm that there was complete mixing of the slurry throughout the profile, again consistent with the theoretical assumption of turbulence overcoming zone settling tendencies. This observation is in agreement with similar observations by Winterwerp et al. (1990).

Allowing for scatter, there was a notable lack of variations in average velocity and Froude No. despite the range of flow rates from 4 -19 L/s.

There was a clear trend for the equilibrium slope to vary with flow rate, but apparently *not* to be dependant on percent solids, at least over the percent solids range experienced of around 54-58%. The trend with Reynolds number was less clear, the lowest value was recorded at the lowest flow rate and the highest at the highest flow rate, but in between there was a lot of scatter.

5. CONCLUSIONS

Different mechanisms of tailings beach formation and development have been studied during a research project carried out at the CTD tailings stack at Peak Gold Mines at Cobar in New South Wales in Australia. The nature of the occurrence of laminar and turbulent flow of tailings slurry over a developing beach were discussed based on observations on the stack. Full-scale flume tests were performed to study the regime and characteristics of channelized flow of non-segregating tailings in equilibrium slope condition. The following conclusions can be drawn from the research work:

- Laminar sheet flow of slurry is always associated with deposition.
- Laminar flow cannot persist over long distances since zone settling within the flowing layer will lead to deposition after a finite period of time.
- Turbulence can overcome zone settling. Thus for long distance travel the tailings forms itself into a concentrated turbulent channel.
- It is postulated that the slope of the channel will be steep enough for the generated turbulence to just overcome zone settling.
- The overall beach slope of the stack is therefore determined by the limiting equilibrium channel slope which is required for a particular tailings, to create the required steady state turbulent total transport flow condition in the self-formed channels.

Based on full-scale, flow-through flume testing, the following observations have been made:

- The average velocity, the Froude No., the velocity profile with depth, and the density profile within the flow are essentially constant for a given slurry and do not vary with flow rate.
- The critical channel slope for full transport of the tailings, and possibly the critical Reynolds number, vary with flow rate.

These latter conclusions are valid for the test work done at Peak Gold Mines. Their validity for other tailings at other mine sites needs to be proven by further testing.

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